Automated Assume-Guarantee Reasoning for Omega-Regular Systems and Specifications

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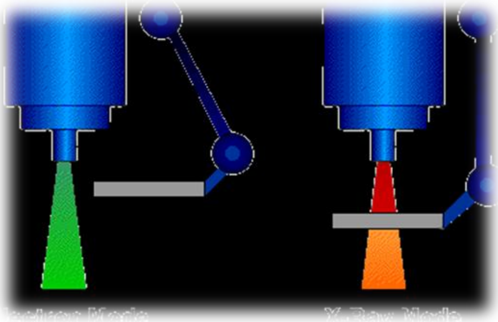
April 13, 2010
Second NASA Formal Methods Symposium

When Failure is Not an Option

Failure is not an option for

- Safety Critical Systems (e.g., X-rays machines)
- Medical Devices (e.g., infusion pumps, …)
- Embedded Software (e.g., cars, airplanes)
- Security Vulnerabilities (e.g., nuclear plants)
- …



Formal software verification is essential to guarantee absence of failures

- Automated techniques include model checking and static analysis …
- which can be used to validate, for example, safety and security, behavior prior to program execution
- and provide objective evidence of safe behavior

Assume Guarantee Reasoning

System M_1 in parallel with system M_2 satisfies specification S

iff there exists an *assumption* A such that

- M_1 in parallel with A satisfies S
- M_2 satisfies the assumption A

$$\frac{M_1 \parallel A \models S \qquad M_2 \models A}{M_1 \parallel M_2 \models S}$$

How to *automatically* find a sufficiently good assumption?!

Related Work

Safety properties

- Giannakopoulou et al. ASE 2002 – computing weakest assumption
- Cobliegh et al. TACAS 2003 – using L* to learn “good-enough” assumption
- Barringer et al. SAVCBS 2003 – AG proof rules, soundness, completeness
- many follow up works to improve algorithms, complexity, applicability, etc.

Liveness properties

- Farzan et al. TACAS 2008 – $L^{\$}$ a learning algorithm for omega-regular languages

- **THIS PAPER**
  - Assume-Guarantee proof rules for reactive (omega-regular) systems
  - Soundness and (in)completeness
  - Two new learning algorithms for infinitary (finite + infinite) languages
  - A unifying framework for learning-based automated AG (see paper)

Outline

Background

- Model of concurrency: LTS, composition, specifications, etc.
- Active learning of regular languages: L^*
- Learning-based Automated Assume Guarantee Framework

Non-Circular Assume Guarantee Rule (AG-NC)

- Soundness and *in-completeness* for omega-regular languages
- Soundness and *completeness* for ∞-regular languages
- Learning algorithms for ∞-regular languages

Circular Assume Guarantee Rule (AG-C)

- Soundness and completeness

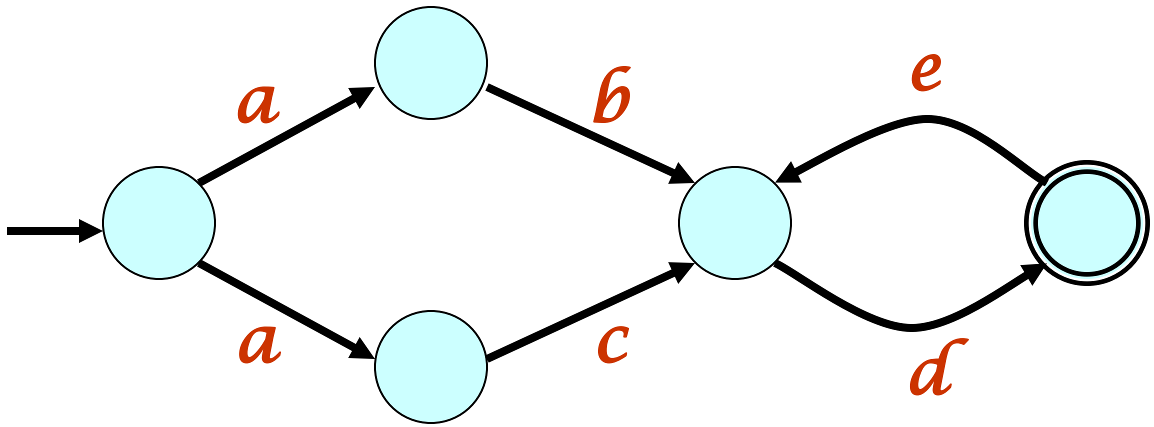
Conclusion and Future Work

Labeled Transition System (LTS)

M = (Q, I, Σ, T)

- Q -- non-empty set of states
- $I \in Q$ an initial state
- Σ -- set of actions (a.k.a, the alphabet)
- $T \subseteq Q \times \Sigma \times Q$ – a transition relation

+ **FA or Buchi acceptance condition**



$\mathcal{M}$

$\Sigma(\mathcal{M}) = \{a,b,c,d,e,f\}$

Operational Semantics

CSP Semantics

- handshake (synchronize) over shared actions
- otherwise, proceed independently (asynchronously)

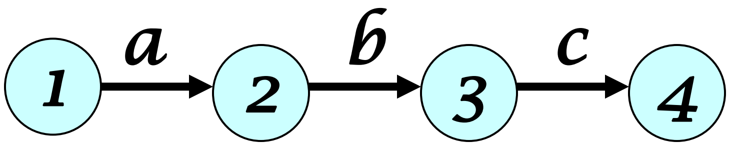
Composition $M_1 \,||\, M_2$ is

- State of $M_1 \,||\, M_2$ is of the form (s_1,s_2), where s_i is a state of M_i

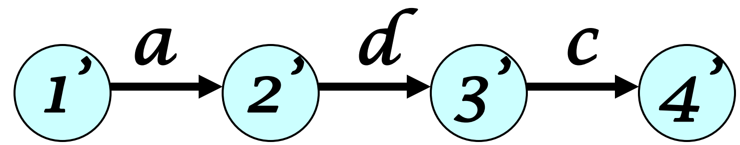
$$\frac{s_1 \xrightarrow{a} t_1 \qquad a \notin \Sigma(\mathcal{M}_2)}{(s_1,s_2) \xrightarrow{a} (t_1,s_2)} \qquad \frac{s_2 \xrightarrow{a} t_2 \qquad a \notin \Sigma(\mathcal{M}_1)}{(s_1,s_2) \xrightarrow{a} (s_1,t_2)}$$

$$\frac{s_1 \xrightarrow{a} t_1 \qquad s_2 \xrightarrow{a} t_2}{(s_1,s_2) \xrightarrow{a} (t_1,t_2)}$$

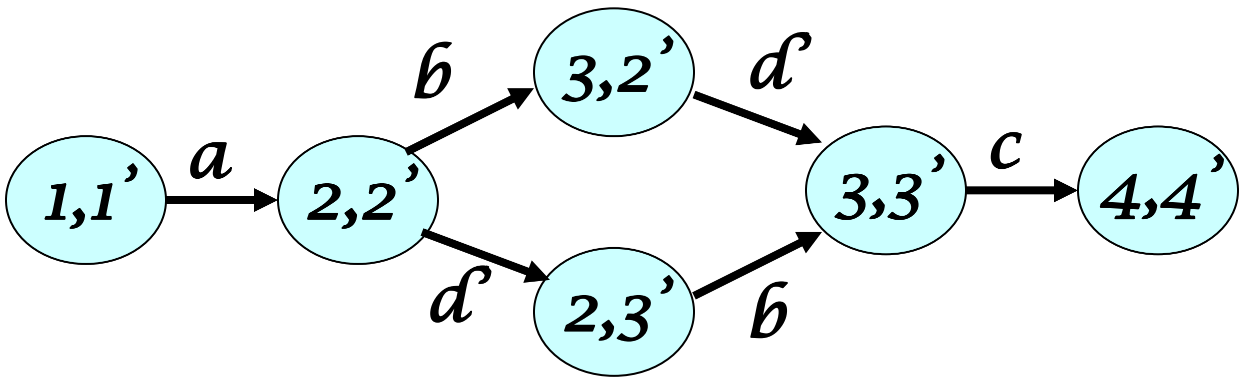
Example of Composition



$\mathcal{M}_1 \quad \Sigma = \{a,b,c\}$



$\mathcal{M}_2 \quad \Sigma = \{a,d,c\}$



$\mathcal{M}_1 \parallel \mathcal{M}_2 \ \Sigma = \{a,b,d,c\}$

L* (Angluin 1987, Rivest & Schapire 1993)

L* learner

$\Sigma(U)$ ⇨

Minimally Adequate Teacher (MAT)

U -- regular language

Membership Query

$s \in U$?

yes/no

Candidate Query

$\mathcal{L}(A) = U$?

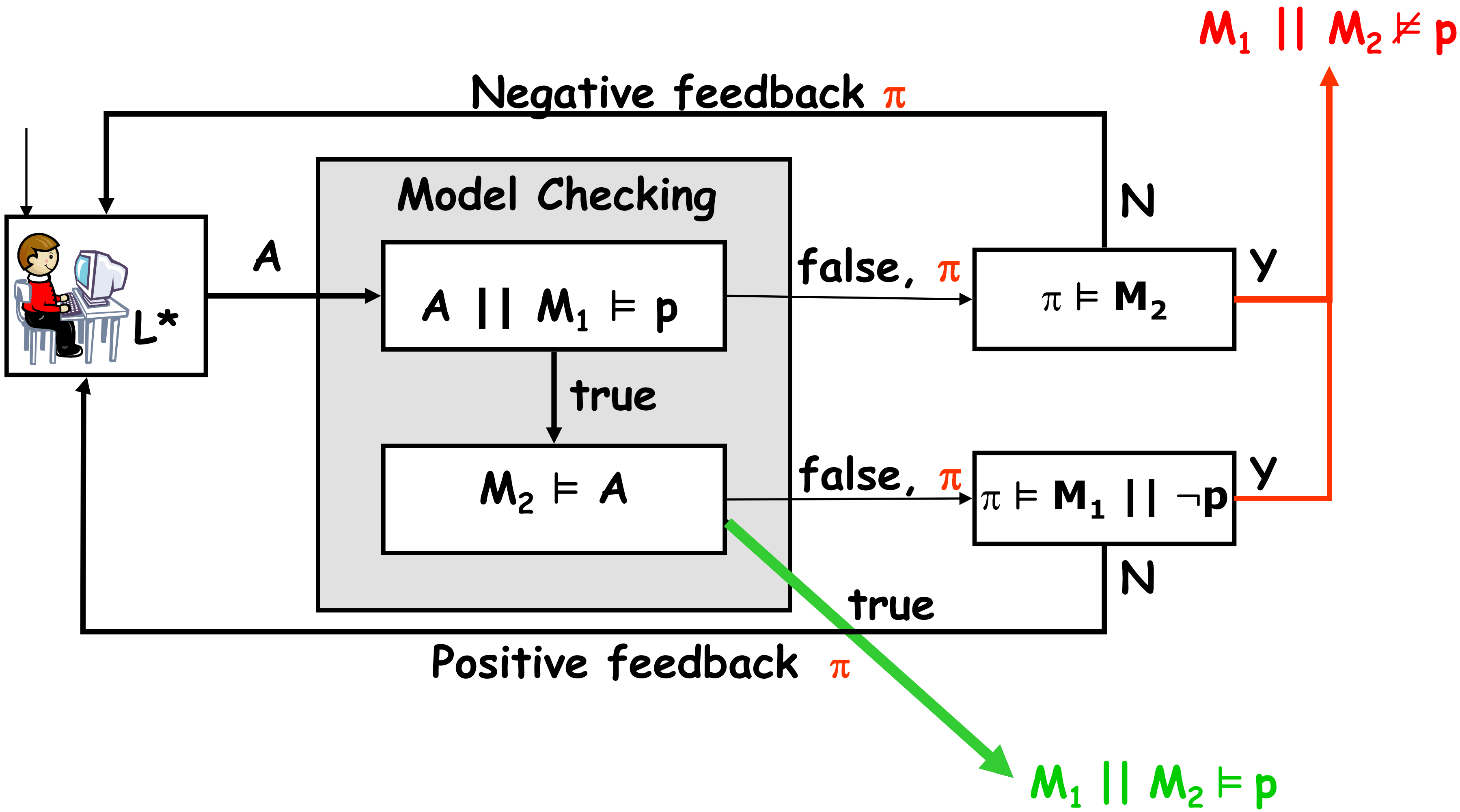
No. $\pi \in U \,\Delta\, \mathcal{L}(A)$

yes. $\mathcal{L}(A) = U$

DFA A

$\mathcal{L}(A) = U$

Assume Guarantee with Learning



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- Learning algorithms for ∞-regular languages

Circular Assume Guarantee Rule (AG-C)

- Soundness and completeness

Conclusion and Future Work

AG-NC: Non-Circular Assume Guarantee Rule

$$L \preceq S \text{ iff } L{\downharpoonright}\Sigma_S \subseteq S$$

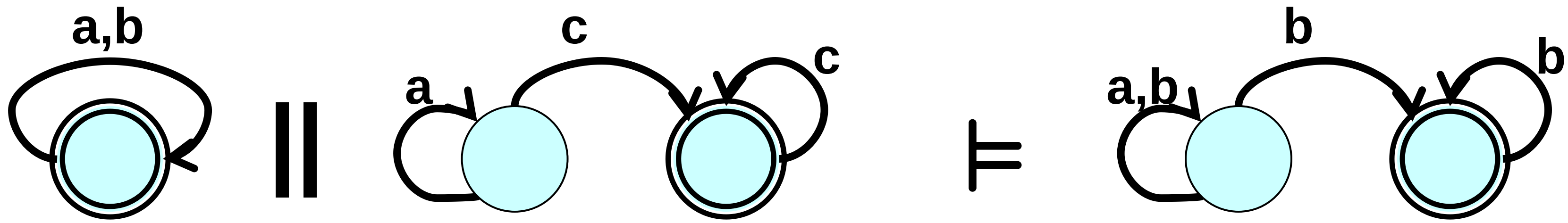
$$\frac{(L_1 \,\|\, L_A) \preceq L_S \qquad L_2 \preceq L_A}{(L_1 \,\|\, L_2) \preceq L_S}$$

$$\Sigma_A = (\Sigma_1 \cup \Sigma_S) \cap \Sigma_2$$

Complete for Safety (regular) properties (Σ^*)

Incomplete for Liveness (omega-regular) properties (Σ^ω)

Proof of Incompleteness (by Counterexample)



Σ_1 = {a, b} Σ_2 = {a, c} Σ_S = {a, b}

$L_1 = (a+b)^\omega$ $L_2 = a^*c^\omega$ $L_S = (a+b)^*b^\omega$

Assumption alphabet: Σ_A = {a}

BUT, there is no assumption $L_A \subseteq \Sigma_A^\omega$ to apply AG-NC

$A_1 = \emptyset \quad L_2 \not\preceq A_1$ $A_2 = a^\omega \quad L_1 \| A_2 \not\preceq L_S$

AG-NC: Infinite Trace Containment

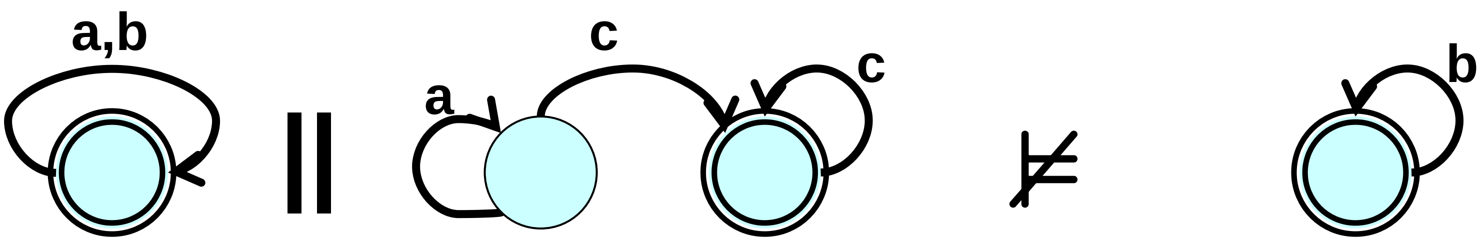
$\mathbf{L} \preceq_\omega \mathbf{S}$ **iff** $\omega(\mathbf{L}\downharpoonright\Sigma_S) \subseteq \omega(\mathbf{S})$

$$\frac{(L_1 \,||\, L_A) \preceq_\omega L_S \qquad L_2 \preceq_\omega L_A}{(L_1 \,||\, L_2) \preceq_\omega L_S}$$

$\Sigma_A = (\Sigma_1 \cup \Sigma_S) \cap \Sigma_2$

NOT SOUND!

Proof of Unsoundness (by Counterexample)



Σ_1 **= {a, b}** Σ_2 **= {a, c}** Σ_S **= {a, b}**

$L_1 = (a+b)^\omega$ $L_2 = a^*c^\omega$ $L_S = b^\omega$

Σ_A **= {a}**

BUT, $L_A = \emptyset$ satisfies all premises of (modified) AG-NC

AG-NC: Relaxing Assumption Alphabet

$$\frac{(L_1 \parallel L_A) \preceq L_S \qquad\qquad L_2 \preceq L_A}{(L_1 \parallel L_2) \preceq L_S}$$

$\cancel{\Sigma_A = \Sigma_1 \; \Sigma \cap \Sigma_2}$

Complete for Safety (regular) properties (Σ^*)

Complete for Liveness (omega-regular) properties (Σ^ω)

Assumption "knows" about internal actions of L_1 and L_2

Not "truly" compositional

AG-NC: Restoring Completeness

Theorem: Let L_1 and L_S be two languages, and Σ_A an alphabet s.t. $\Sigma_1 \cup \Sigma_A = \Sigma_1 \cup \Sigma_S$. Then, $L_A = \mathcal{C}((L_1 \,||\, \mathcal{C}(L_S))\lfloor\Sigma_A)$ is the *weakest* assumption such that $L_1 \,||\, L_A \preceq L_S$

Corollaries:

AG-NC is complete for any class of languages closed under *projection* and *complement*

AG-NC is complete for Σ^*

AG-NC is complete for $\Sigma^\infty = \Sigma^* \cup \Sigma^\omega$

Need a learning algorithm for Σ^∞!

Learning Infinitary Language U: Approach 1

Use L* and L$^{\$}$ *simultaneously* to learn a DFA *D* and a BA *B* such that $\mathcal{L}(\text{DFA}) = {}^*(U)$ and $\mathcal{L}(\text{BA}) = \omega(U)$

Assume M is a MAT for U

Use M to answer membership queries until *both* learners generate a candidate query

Use M to verify the candidate query: $\mathcal{L}(D) \cup \mathcal{L}(B) = U$

- on success, stop
- if counterexample is finite, send to L* and resume until next DFA candidate
- if counterexample is infinite, send to L$^{\$}$ and resume until next BA candidate

Two learners. Possibly a lot of redundancy.

Learning Infinitary Language U: Approach 2

Use L$^{\$}$ to learn U.τ^ω, where τ is a "fresh" symbol not in Σ_U

Assume M is a MAT for U

To answer a membership query infinite word s

- if s = t.τ^ω and t $\in \Sigma_U^\infty$ then ask M whether t $\in$ U and forward answer back
- Otherwise, answer "no"

To answer a candidate query with candidate BA *C*

- if $\mathcal{L}$(C) $\nsubseteq \Sigma_U^\infty.\tau^\omega$ return $\pi \in \mathcal{L}$(C) $\setminus \Sigma_U^\infty.\tau^\omega$
- otherwise, forward candidate query *($\mathcal{L}$(A)$\downharpoonleft\Sigma$), ω($\mathcal{L}$(A)$\downharpoonleft\Sigma$) to M

Single learner, BUT larger alphabet

Circular AG-rule (AG-C): Summary

$$\Sigma_{A1} = \Sigma_{A2} = (\Sigma_1 \cap \Sigma_2) \cup \Sigma_S$$

$$\frac{L_1 \parallel L_{A1} \preceq L_S \qquad L_2 \parallel L_{A2} \preceq L_S \qquad \mathcal{C}(L_{A1}) \parallel \mathcal{C}(L_{A2}) \preceq L_S}{L_1 \parallel L_2 \preceq L_S}$$

Complete for Safety (regular) properties (Σ^{∞})

Complete for Liveness (omega-regular) properties (Σ^{ω})

BUT need to learn 2 assumptions AND assumption alphabet is larger

Learning-Based AG (LAG) Framework

Conformance	Rule	$\mathcal{A}$	Learner(s)	Oracle(s)	Checker
Regular Trace Containment	**AG-NC** [1]	DFA	$P_1 = P(\mathbf{L}^*)$	$Q_1 = Q(L_1, L_S, \Sigma_{NC})$	$V_{NC}(L_1, L_2, L_S)$
Regular Trace Containment	**AG-C** [2]	DFA	$P_1 = P_2 = P(\mathbf{L}^*)$	$Q_1 = Q(L_1, L_S, \Sigma_C)$ $Q_2 = Q(L_2, L_S, \Sigma_C)$	$V_C(L_1, L_2, L_S)$
∞-regular Trace Containment	**AG-NC**	DFA $\times$ BA	$P_1 = P(\mathbf{L})$	$Q_1 = Q(L_1, L_S, \Sigma_{NC})$	$V_{NC}(L_1, L_2, L_S)$
∞-regular Trace Containment	**AG-C**	DFA $\times$ BA	$P_1 = P_2 = P(\mathbf{L})$	$Q_1 = Q(L_1, L_S, \Sigma_C)$ $Q_2 = Q(L_2, L_S, \Sigma_C)$	$V_C(L_1, L_2, L_S)$
ω-regular Trace Containment	**AG-NC**	DFA $\times$ BA	$P_1 = P(\mathbf{L})$	$Q_1 = Q(L_1, L_S, \Sigma_{NC})$	$V_{NC}(L_1, L_2, L_S)$
ω-regular Trace Containment	**AG-C**	BA	$P_1 = P_2 = P(\mathbf{L}^\omega)$	$Q_1 = Q(L_1, L_S, \Sigma_C)$ $Q_2 = Q(L_2, L_S, \Sigma_C)$	$V_C(L_1, L_2, L_S)$

[1] Cobleigh, Giannakopoulou, Pasareanu, TACAS'03

[2] Barringer, Giannakopoulou, Pasareanu, SAVCBS'03

The last four rows are contributions of THIS PAPER

NEW!

Conclusion and Future Work

Compositional approach to verification is fundamental for scalability!

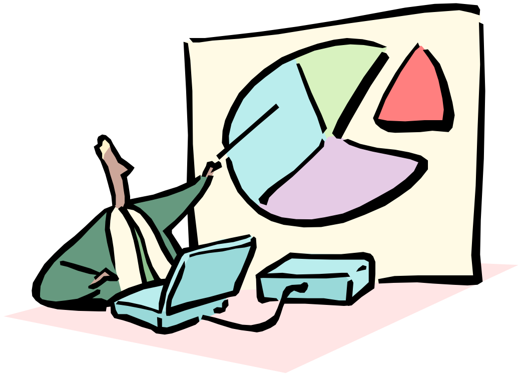
Automated AG for Liveness (omega-regular) properties

- Non-Circular Rule: soundness, (in)completeness
- Circular rule – remains sound and complete
- Two new learning algorithms for infinitary languages

Unified Framework for Learning-based Assume Guarantee Reasoning

Future Work

- implementation and empirical evaluation
- experiments with other learning algorithms



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